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Effects of introduced earthworms on the productivity of New Zealand pastures[1])

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With one figure

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1. Introduction

Pasture improvement associated with earthworm activity has long been recognised on a wide range of New Zealand soils (Hamblyn & Dingwall 1945, Nielson 1951a, 1951b, 1953, Waters 1951, Sears & Evans 1953, Richards 1955, Stockdill 1959, 1966, Stockdill & Cossens 1966). Nielson (1951b, 1953), comparing eight soils in boxes with and without *A. caliginosa*, measured increases of 28—120 % from mixed swards. Warters (1951), from pot trials, reported a 77 % increase for pure ryegrass and 113 % for the ryegrass component of a mixed sward.

Stockdill (1959, 1966) measured, under field conditions, a 72 % increase in spring pasture production and reported soil chemical changes following the introduction of *A. caliginosa* to an otherwise highly improved pasture on a yellow-brown earth soil near Hindon in Otago, Later, more detailed pasture measurements from this field and soil physical changes on this and other sites were reported by Stockdill & Cossens (1966).

2. Effects of introduced earthworms on pasture yields

Earthworms, *A. caliginosa*, were introduced to the Hindon field in October 1949 when the pasture was six years old and quite high producing. Four years later, in September 1953, green patches of earlier spring growth showed up at each point of introduction. The 72 % pasture production increase was measured in three cuts taken in spring 1954 from 11 year old pasture.

Once established, the earthworms advanced about 10 m per year across the field and commencing in spring 1965, G. G. Cossens used the rate of growth technique (Lynch 1960) to measure production from zones (1) where earthworms had been established for some 10 years, (2) where they were entering during 1965/66 and (3) where there were still no worms.

In the 1965/66 season, the yield from Zone 1 with worms established was 29 % greater than for Zone 3 with no worms (Table 1). For Zone 2 where worms were entering, the increase was 19 %, largely due to a 45 % increase in autumn 1966 when there was a general spread of earthworm activity across the zone. In spring 1966, the yields from Zones 1 and 2 with worms were respectively 26 and 30 % greater than from Zone 3 without worms. Summer and autumn yields were adversely affected by extremely dry conditions. Summer yield from Zone 1 was low relative to the other zones, possibly because it was more exposed to drying winds. Worms were entering Zone 3 by autumn 1967. Even so the yields from Zones 1 and 2 were 9 % and 23 % more than from Zone 3.

Without earthworms this 23 year old pasture, adequately limed and fertilised, was producing 8—9 t ha^{-1} of dry matter. It had a characteristic harsh appearance and was rather

[1]) Contribution to the Darwin Centenary Symposium on Earthworm Ecology, Grange-over-Sands (1981).

Table 1. Dry matter yields of pasture and % increase over zone without worms — Hindon (September to May 1965/66 and 1966/67)

	Zone 1		Zone 2		Zone 3
	Worms Established		Worm Entering 1965/66		No Worms
	Yield kg ha^{-1}	Increase %	Yield kg ha^{-1}	Increase %	Yield kg ha^{-1}
Spring 1965	4,100	26	3,610	11	3,260
Summer 65/66	4,780	27	4,120	9	3,760
Autumn 1966	3,220	35	3,450	45	2,380
Total 1965/66	**12,100**	29	**11,180**	19	**9,400**
Spring 1966	4,230	26	4,360	30	3,350
Summer 66/67	2,350	—16	3,090	10	2,800
Autumn 1977	1,910	16	2,180	32	1,650
Total 1966/67	**8,490**	9	**9,630**	23	**7,800**

open with the usual excess of dead plant material and old animal faeces that typifies pastures without worms. Where earthworms were active, the dead litter disappeared and a close vigorous sward developed with production increasing to as much as 12 t ha^{-1} of dry matter. Similar pasture responses to earthworm activity have been observed on a wide range of soils throughout New Zealand.

3. Soil changes

Topsoil profiles from the Hindon pasture when it was 23 years old illustrate the pronounced soil changes brought about by earthworm activity.

Without worms, decomposition is extremely slow and there is a definite break in nutrient cycling. With no mixing of the soil, lime, fertilizers and insecticides remain as a surface veneer and beneath this the soil lacks organic matter and plant nutrients. It is compact, dry and poorly structured. Moisture penetration and plant root development are severely restricted. The soil resembles a laminated mor with a shallow organic horizon although it is not strongly acid.

In contrast the soil with worms, sampled about 20 m away, is a strongly granular mull with dung and dead plant residues incorporated into the top soil and a much deeper organic matter distribution. Lime, fertilizers and insecticides are mixed through the soil and soil structure, infiltration of rainfall and moisture holding capacity are all improved giving a more friable and moister top soil with greater root development.

Between these zones the invading earthworm population is actively burying and breaking down the accumulated surface organic layer. The consequent rapid release of nutrients may account for a greater pasture response during this invasion phase.

4. Chemical effects

Soil analyses (Stockdill 1959, 1966) have confirmed the improved verticle distribution of organic material, plant nutrients, lime and insecticides in soils with worms. Loss on ignition, organic carbon, nitrogen, cation exchange capacity and exchangeable bases have all been consistent with transfer from the surface to the soil beneath. On soils without worms, the surface veneer effect can be clearly seen where lime has been applied as a topdressing. The lime can be found many years later within or beneath the surface organic layer. At rates of application as high as 5 t ha^{-1}, pH and calcium levels are not affected below 2.5 cm even after 4—5 years.

5. Physical effects

Cossens examined the physical properties of soils with and without worms at six sites on various soil types including the Hindon field (Stockdill 1966, Stockdill & Cossens 1966). There were marked increases in field capacity, available moisture and infiltration rates in the soils with worms. These were associated with increased organic matter and improved soil structure.

Two sites (Table 2) were known to have had 10 years of earthworm activity. Site 1, the Hindon field, was on a hygrous upland yellow brown earth and Site 2 at Nenthorn on a sub-hygrous yellow-grey earth. The field capacity of the soils with worms was higher at both sites. The soils with worms had a 17% greater capacity to hold moisture in the top 30 cm than those without.

The 1,5 MPa (15 bar) moisture retention (wilting point) and bulk density of the soils with worms remained about the same. It follows that, with their higher field capacity, the soils with worms were capable of holding a greater amount of available moisture. The increase in available moisture for the top 30 cm of soil depth at both sites was 18 mm. Both the intial five hour intake of water and the basic infiltration rate per hour were almost doubled. Worms increased the basic infiltration rate by 12 to 13 mm per hour.

These greatly increased rates of water intake reduce run-off and the risk of erosion and flooding. Sharpley, Syers & Springett (1979) have shown on a quite unrelated soil that chemical elimination of earthworms doubled annual run-off from a 13° slope from 1,650 m^3 ha^{-1} to 3,210 m^3 ha^{-1}.

The macroporosity of soils with worms decreased considerably. This may be difficult to reconcile with increased infiltration but soil structure has improved with earthworm activity and there are probably fewer macropores of greater diameter in the soil with worms. This would allow freer movement of water down the profile, particularly through the top 30 cm or so.

6. Root development

Improved soil structure, deeper incorporation of organic material and plant nutrients and better penetration of moisture have contributed to greatly improved plant root development. This reduces susceptibility to drought and allows better uptake of nutrients. Without worms much of the root system is found in the surface organic mat and the top 15 cm of soil.

Table 2. Physical analyses and soil moisture data for sites with and without worms

	Hindon			Nenthorn	
	Depth cm	Without Worms	With Worms	Without Worms	With Worms
Field capacity % by weight	0—10	42.0	51.7	33.2	36.6
	0—30	36.6	42.7	28.2	33.1
1,5 MPa retention*) % by weight	0—10	15.6	16.2	10.2	11.7
	0—30	13.5	13.7	9.0	9.6
Bulk density g cc^{-1}	0—10	0.68	0.86	0.90	0.99
	0—30	0.96	0.96	1.09	1.13
Available moisture mm	0—10	18.3	31.0	21.1	25.1
	0—30	66.0	84.1	63.0	80.8
Macro porosity %	0—10	44.9	21.5	45.3	25.5
	0—30	29.3	22.7	31.4	19.6
Organic carbon % by volume	0—10	3.54	4.46	2.60	3.68
	0—30	2.38	2.97	2.10	2.80
Infiltration mm	5 hr intake	289.6	608.3	165.1	299.5
	Basic rate hr^{-1}	14.0	26.4	13.0	25.4

*) 1 bar = $1 \cdot 10^5$ Pa [Pascal]; 1,5 MPa = 15 bar [wilting point].

7. Undesirable effects

Some less desirable effects are associated with earthworm activity. Removal of the surface organic mat and casting of soil into the base of the pasture results in increased soil intake by stock. HEALY & LUDWIG (1965) have shown that teeth wear is directly related to soil ingestion.

Under wet conditions surface pugging is more likely on pastures with worms as is difficulty in traversing them with vehicles.

Increased infiltration of water may result in increased leaching. STOCKDILL (1966) has shown lower *p*H and calcium levels following many years of earthworm activity and higher levels of maintenance liming may therefore be necessary on soils with worms.

8. Earthworm species and distribution

There are over 190 earthworm species in New Zealand (LEE 1959) but only a few introduced species are regarded as beneficial. *Allolobophora caliginosa* is the most widely distributed and where present it generally predominates. Measurement of earthworm effects has been mainly confined to this species. Others that appear to have similar effects are *A. tuberculata*, *A. rosea*, *A. chlorotica*, *A. trapezoides* and *A. longa*. *A. longa* could be more adaptable to coarse textured soils. *Octolasium cyaneum* is less effective and *Lumbricus rubellus*, although widely distributed, is found mainly under dung pats and in highly organic or wet areas. Other species, mainly native, occur under pasture, sometimes in quite high numbers, up to 200 m^{-2}, without observable beneficial effects.

The invasion of New Zealand pastures by beneficial species has been largely accidental. Few land developers have deliberately introduced earthworms as part of their development programmes. Most improved pastures close to earlier European settlement have been populated for many years. In more remote areas, populations are usually found close to old homesteads but vast areas of otherwise highly improved pasture have remained unpopulated. Many undeveloped soils are too low in calcium to support beneficial species (NIELSON 1951). Other areas are too dry without irrigation.

Populations of *A. caliginosa* under high producing grazed pastures can be as high as 2,000 m^{-2}, but densities of 500—1,000 m^{-2} are more common. Lower populations are often associated with low calcium levels and applications of 2.5 t ha^{-1} of lime have increased worm numbers by 50 %. Populations are usually lower in ungrazed areas and in cultivated soils.

9. Methods of earthworm introduction

In early experimental introductions, worms were gathered and placed in the soil under the deficient pasture. Later, blocks of turf containing worms were dug in at strategic points in the hope that the worms would ultimately spread. There was little prospect of gaining uniform coverage of large areas using these methods.

With more knowledge of the requirements and behaviour of the beneficial species, *A. caliginosa*, a more acceptable method was developed. It is known that high calcium levels and adequate moisture favour earthworm activity and reproduction and that under moist conditions most of the worms are close to the soil surface and move down quite quickly as soils dry out. Introduced worms were known to take several years to establish at the point of introduction but once established to spread at about 10 m y^{-1}.

Trials confirmed that if turfs from a highly populated source were placed on the surface the worms move quickly into the soil beneath. Localised applications of lime, 0.5 kg to a square metre at each point, ensured adequate calcium for initial establishment and the 4—5 years normally required for the worms to populate the limed patch. Under moist conditions, establishment was very nearly as successful as from digging in the turfs.

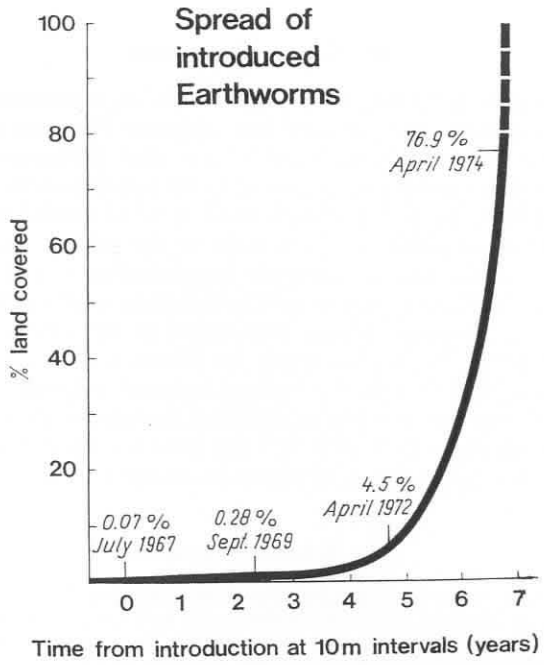

Fig. 1. Spread of *A. caliginosa* introduced at 10 m intervalls.

If turfs are placed at 10 m spacings in rows 10 m apart, complete coverage can be expected within 6—7 years, a little sooner under high rainfall, and longer in drier areas. Where calcium levels are marginal, a broadcast application of lime at 2.5 t ha^{-1} is recommended in the fourth year to hasten population expansion and complete coverage.

The very limited movement of worms in the first four years of establishment followed by rapid spread to complete coverage by the 6th to 7th year has been confirmed by G. G. Cossens in a recent study of *A. caliginosa* introduced at 10 m intervals (Fig. 1). At first the turfs were lifted with spades and the lime was spread and the turfs placed by hand. Placing the turfs grass side down prevented them from taking root, ensured good contact with the ground and provided a food supply of semi-rotting pasture for the worms.

This method was acceptable for smaller areas but for wider application there was a need for mechanisation. Mr. G. A. Martin, a Ministry of Agriculture & Fisheries Engineer at the New Zealand Agricultural Engineering Institute, designed machines for cutting turfs and distributing them with lime. The turf cutting machine cuts turf blocks 200 mm square and 50—75 mm deep. Cleats on a wheel make transverse cuts at 200 mm intervals and disc coulters and a cutting shoe cut the sides and bottom. The turf blocks are left lying in the furrow from which they are generally stacked in heaps of four for loading on to a vehicle.

The distributor has a 1 m wide lime-sowing box and a metal chute down which the turf blocks are propelled by a chain with cleats. A chain from the ground wheel is fitted with a small bar on one link and is so geared that it activates the lime sower and turf chute every 10 metres. A square metre of lime is sown and a turf block dropped on it, grass side down. Using this machinery, two men can introduce worms to 25 ha day^{-1}; 100 turf blocks and 50 kg of lime are required ha^{-1}.

The work should be done when soils are moist enough for the maximum number of worms to be in the top 50—75 mm of the source area and when the deficient area is likely to remain moist enough for initial colonisation.

10. Economic benefits

In New Zealand, earthworm introduction is almost certainly the most profitable development opportunity open to farmers with unpopulated pastures. They can expect an increase in carrying capacity of 2.5 stock units ha^{-1} 6 to 7 years after worms are introduced. A recent cost/benefit analysis shows the present value of future benefits to exceed the present value of all costs by \$ 194 ha^{-1}. Each \$ 1 of costs earns \$ 3.5 of benefit in present value terms after discounting future benefits and costs back to the present time at 10% y^{-1}. Costs ha^{-1} were \$ 10 in year 1 for labour, transport, lime, machinery and turfs; \$ 42.50 in year 4 for 2.5 t ha^{-1} of lime; \$ 50 over years 6 and 7 for 2.5 extra stock units, and \$ 1.80 from year 5 onwards for extra maintenance liming. Discounted at 10% these costs have a present value of \$ 76 ha^{-1}. Extra income was based on 2.5 stock units ha^{-1} from years 6 and 7 onwards at a gross margin of \$ 20 SU^{-1} y^{-1} giving a present value for the benefits of \$ 270.

New Zealand probably has in excess of 2 million hectares of pasture that could benefit from earthworm introduction. At 2.5 SU ha^{-1} the extra 5 million stock units that could be carried could earn over \$ 200 million per annum in overseas exchange.

11. Acknowledgements

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Synopsis: Subject review article

STOCKDILL, S. M. J., 1982. Effects of introduced earthworms on the productivity of New Zealand patures. Pedobiologia **24**, 29—35.

Comparison of pastures with and without *A. caliginosa* has demonstrated substantial increases in pasture production associated with pronounced chemical and physical changes in the soils with worms. Observations suggest that several other pecies have similar benefical effects.

The obvios changes resulting from earthworm activity are the incorporation of organic matter from the soil surface and improved open friable structure of the soil. Soils are moister and plant root development improves. Analyses show that lime, plant nutrients and insecticides are also mixed through the soil. Infiltration rate doubles, moisture holding capacity increases 17 % and available moisture increases by 18 mm for the top 30 cm of the soils tested. Better infiltration reduces run off and risk of erosion and flooding.

A method of introducing earthworms to unpopulated pastures has been developed and found sucessful. Mechanisation of this operation has made possible the treatment of larger areas. Cost benefit studies indicate that earthworm introduction presents a highly profitable development opportunity for farmers with unpopulated pastures.

Key words: Allolobophora caliginosa; earthworm, activity, reproduction, introduction, distribution; pasture, improvement, production, economy, benefit, cost effect, studies; profit, development; soil, structure, macroporosity, nutrient, cycle; organic matter, distribution; root, development; infiltration, moisture, holding capacity, erosion, flooding; turf block, cutting machine; lime ↔ calcium, level, application.